

First Observation of Doubly Cabibbo-Suppressed Decay of a Charmed Baryon:

$$\Lambda_c^+ \rightarrow p K^+ \pi^-$$

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We report the first observation of the decay $\Lambda_c^+ \rightarrow pK^+\pi^-$ using a 980 fb^{-1} data sample collected by the Belle detector at the KEKB asymmetric-energy e^+e^- collider. This is the first doubly Cabibbo-suppressed decay of a charmed baryon to be observed. We measure the branching ratio of this decay with respect to its Cabibbo-favored counterpart to be $\mathcal{B}(\Lambda_c^+ \rightarrow pK^+\pi^-)/\mathcal{B}(\Lambda_c^+ \rightarrow pK^-\pi^+) = (2.35 \pm 0.27 \pm 0.21) \times 10^{-3}$, where the uncertainties are statistical and systematic, respectively.

Several doubly Cabibbo-suppressed (DCS) decays of charmed mesons have been observed. Their measured branching ratios with respect to corresponding Cabibbo-favored (CF) decays play an important role in constraining models of the decay of charmed hadrons and in the study of flavor- $SU(3)$ symmetry [1]. Because of the smaller production cross sections for charmed baryons, DCS decays of charmed baryons have not yet been observed, and only an upper limit, $\mathcal{B}(\Lambda_c^+ \rightarrow pK^+\pi^-)/\mathcal{B}(\Lambda_c^+ \rightarrow pK^-\pi^+) < 0.46\%$ with 90% confidence level, has been reported by the FOCUS Collaboration [2]. Theoretical calculations of DCS decays of charmed baryons have been limited to two-body decay modes [3, 4].

In this letter, we report the first observation of the DCS decay $\Lambda_c^+ \rightarrow pK^+\pi^-$ and the measurement of its branching ratio with respect to its counterpart CF decay $\Lambda_c^+ \rightarrow pK^-\pi^+$ [5]. Unlike charmed meson decays, internal W emission and W exchange are not suppressed for charmed baryon decays. In previous studies of CF or singly Cabibbo-suppressed (SCS) decays of Λ_c^+ and Ξ_c^0 , direct evidence of W exchange and internal W emission has been observed [6–10]. When we consider that W exchange is prohibited in $\Lambda_c^+ \rightarrow pK^+\pi^-$ but allowed in $\Lambda_c^+ \rightarrow pK^-\pi^+$, the contribution of W exchange to Λ_c^+ decays can be estimated by comparing the measured branching ratio with the naïve expectation [2], $\tan^4 \theta_c$ (0.285%), where θ_c is the Cabibbo mixing angle [11] and $\sin \theta_c = 0.225 \pm 0.001$ [12]. This approach does not take into account effects of flavor- $SU(3)$ symmetry breaking.

We analyze data taken at or near the $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, $\Upsilon(4S)$, and $\Upsilon(5S)$ resonances collected by the Belle detector at the KEKB asymmetric-energy e^+e^- collider [13]. The integrated luminosity of the data sample is 980 fb^{-1} . The Belle detector is a large-solid-angle magnetic spectrometer comprising a silicon vertex detector (SVD) [14], a central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL) located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. The detector is described in detail elsewhere [15]. The combined particle identification (PID) likelihoods, $\mathcal{L}(h)$ ($h = p, K$, or π), are derived from ACC and TOF measurements and dE/dx measurements in CDC. The discriminant $\mathcal{R}(h|h')$, defined as $\mathcal{L}(h)/(\mathcal{L}(h) + \mathcal{L}(h'))$, is the ratio of likelihoods for h and h' identification. The electron likelihood ratio, $\mathcal{R}(e)$, for e and h identification is derived from ACC, CDC, and ECL measurements [16]. We use samples of $e^+e^- \rightarrow c\bar{c}$ Monte Carlo (MC) events, which are generated with PYTHIA [17] and EvtGen [18] and propagated by GEANT3 [19] to simulate the detector performance, to estimate reconstruction efficiencies and to study backgrounds.

In this analysis, our selection criteria follow mostly

those typically used in other charmed hadron studies at Belle (for example, Ref. [1, 8, 10]). However, our final criteria are determined by a figure-of-merit (FoM) study performed using a control sample of the CF decay ($\Lambda_c^+ \rightarrow pK^-\pi^+$) in real data, together with sidebands to the DCS signal region. We use this blinded study to optimize the FoM, defined as $n_{\text{sig}}/\sqrt{n_{\text{sig}} + n_{\text{bkg}}}$, where n_{sig} is the fitted yield of the control sample multiplied by the presumed ratio of the DCS and CF decays (0.0025), and n_{bkg} is the number of background events from the sideband region in the DCS decay.

A Λ_c^+ candidate is reconstructed from the three charged hadrons, and all charged tracks are required to have a distance of closest approach to the interaction point (DOCA) less than 2.0 cm and 0.1 cm in the beam direction (z) and in the transverse (r - ϕ) direction, respectively. The number of SVD hits is also required to be at least one, both in the z and r - ϕ directions, for each of three charged particles. The charged particles are identified by the PID measurements: $\mathcal{R}(p|h) > 0.9$ for both $h = \pi$ and K is required for charged protons, $\mathcal{R}(K|p) > 0.4$ and $\mathcal{R}(K|\pi) > 0.9$ are required for charged kaons, $\mathcal{R}(\pi|p) > 0.4$ and $\mathcal{R}(\pi|K) > 0.4$ are required for charged pions, and $\mathcal{R}(e) < 0.9$ is required for all charged particles. The identification efficiencies of p , K , and π are 75%, 75%, and 95%, respectively, for the typical momentum range of the decays. Probabilities of misidentifying h as h' , $P(h \rightarrow h')$, are 8% ($P(p \rightarrow K)$), 5% ($P(p \rightarrow \pi)$), 11% ($P(K \rightarrow \pi)$), 2% ($P(K \rightarrow p)$), 2% ($P(\pi \rightarrow K)$), and less than 1% ($P(\pi \rightarrow p)$) for the typical momentum range. To suppress combinatorial backgrounds, especially from B meson decays, we place a requirement on the scaled momentum: $x_p > 0.53$, where x_p is defined as $p^*/\sqrt{E_{\text{cm}}^2/4 - M^2}$; here, E_{cm} is the total center-of-mass energy, p^* is the momentum in the center-of-mass frame, and M is the mass of the Λ_c^+ candidate. In addition, the χ^2 value from the common vertex fit of the charged tracks must be less than 40.

Figures 1 and 2 show invariant mass distributions, $M(pK^-\pi^+)$ (CF) and $M(pK^+\pi^-)$ (DCS), with the final selection criteria. DCS decay events are clearly observed in $M(pK^+\pi^-)$. We perform a binned least- χ^2 fit to the two distributions from 2.15 GeV/ c^2 to 2.42 GeV/ c^2 with 0.01 MeV/ c^2 bin width, and the figures are drawn with merged bins. The probability density functions (PDFs) for the fits are the sum of two Gaussian distributions, with a common central value, to represent the signals, and polynomials of fifth and third order for the combinatorial backgrounds in the $M(pK^-\pi^+)$ and $M(pK^+\pi^-)$ distributions, respectively. In the fit to $M(pK^+\pi^-)$, the resolution and central value of the signal function are fixed to be the same as those found from the fit to $M(pK^-\pi^+)$. The reduced χ^2 values ($\chi^2/d.o.f$) of the fits are 1.03 (27749/26989) and 1.01 (27131/26995) for the CF and DCS decays, respectively. From the fit results, the signal yields of $\Lambda_c^+ \rightarrow pK^-\pi^+$ and $\Lambda_c^+ \rightarrow pK^+\pi^-$ de-

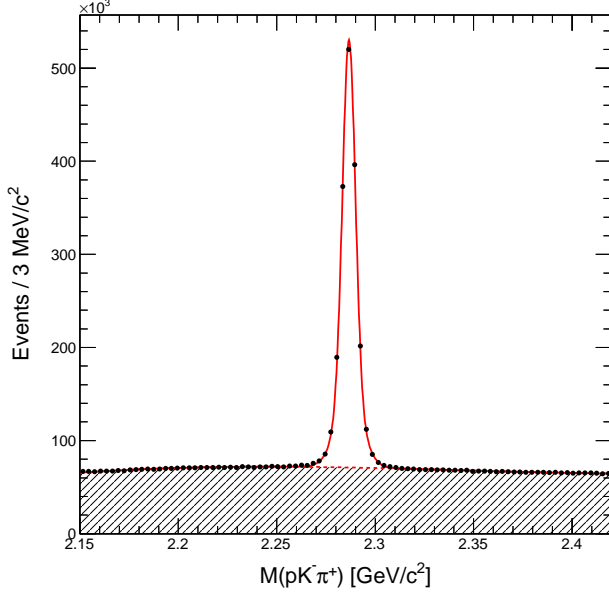


FIG. 1. Distribution of $M(pK^-\pi^+)$. The curves indicate the fit result: the full fit model (solid) and the combinatoric background only (dashed).

cays are determined to be $(1.452 \pm 0.015) \times 10^6$ events and 3587 ± 380 events, respectively, where the uncertainties are statistical. There is a small excess above background on the right side of the Λ_c^+ peak (around $2.297 \text{ GeV}/c^2$) in the DCS spectrum of Fig. 2. We attribute this to a statistical fluctuation as no known process would make such a narrow feature at this position even when possible particle misidentification, such as the misidentification of both the K and the π , is taken into account.

The DCS decay has a peaking background from the SCS decay $\Lambda_c^+ \rightarrow \Lambda K^+$ with $\Lambda \rightarrow p\pi^-$, which has the same final state topology. However, because of the long Λ lifetime, many of the Λ vertexes are displaced by several centimeters from the main vertex so the DOCA and χ^2 requirements suppress most of this background. The remaining SCS-decay yield is included in the signal yield of $\Lambda_c^+ \rightarrow pK^+\pi^-$ decay and is estimated via the relation

$$\mathcal{N}(SCS; \Lambda \rightarrow p\pi^-) = \frac{\epsilon(SCS; \Lambda \rightarrow p\pi^-)}{\epsilon(CF)} \frac{\mathcal{B}(SCS; \Lambda \rightarrow p\pi^-)}{\mathcal{B}(CF)} \mathcal{N}(CF), \quad (1)$$

where $\mathcal{N}(CF)$ is the signal yield of the CF decay, $\mathcal{B}(SCS; \Lambda \rightarrow p\pi^-)/\mathcal{B}(CF) = (0.61 \pm 0.13)\%$ is the branching ratio [12], and $\epsilon(SCS; \Lambda \rightarrow p\pi^-)/\epsilon(CF) = 0.023$ is the relative efficiency found using MC samples. This calculation gives a yield of 208 ± 78 events from this source, where the uncertainty is estimated by comparing the signal yields from this calculation and a fit to $M(pK^+\pi^-)$ with loosened selection criteria for the ver-

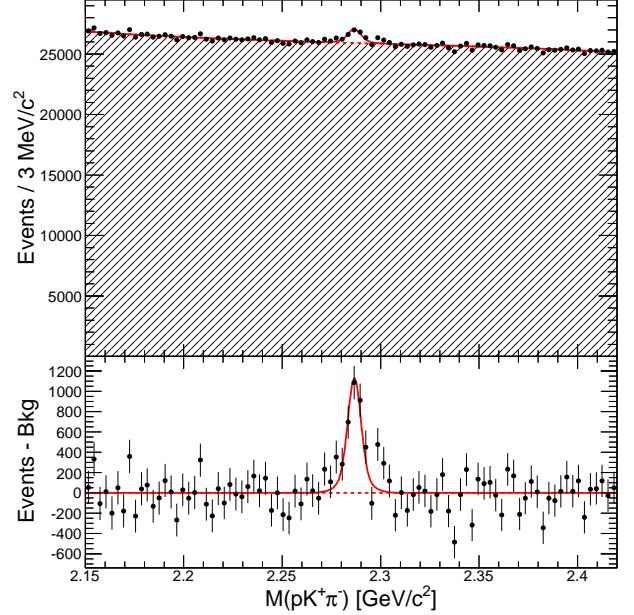


FIG. 2. Distribution of $M(pK^+\pi^-)$ (top) and residuals of data with respect to the fitted combinatorial background (bottom). Curves are drawn as described in Fig. 1.

tex point and Λ selection in $M(p\pi^-)$. After subtraction of this SCS component, the signal yield of the DCS decay is $3379 \pm 380 \pm 78$, where the first uncertainty is statistical and the second is systematic due to this subtraction.

To estimate the statistical significance of the DCS signal, we exclude the SCS signal by vetoing events with $1.1127 \text{ GeV}/c^2 < M(p\pi^-) < 1.1187 \text{ GeV}/c^2$. The significance is estimated as $\sqrt{-2 \ln(\mathcal{L}_0/\mathcal{L})}$, where \mathcal{L}_0 and \mathcal{L} are the maximum likelihood values from binned maximum likelihood fits with the signal yield fixed to zero and allowed to float, respectively. The calculated significance corresponds to 9.4σ .

We calculate the reconstruction efficiency using a mixture of subchannels weighted with their corresponding branching ratios for the CF decay taken from the PDG [12]. For the DCS decay, we assume subchannels $pK^*(892)^0$, $\Delta(1232)^0 K^+$, and non-resonant decay with 0.23, 0.18, and 0.59 branching fractions, respectively. These values are chosen as they are the branching fractions for the corresponding subchannels of the CF decay adjusted for the fact that $\Lambda(1520)$ cannot be produced in the DCS decay. To estimate the uncertainty arising from the assumed mix of intermediate states of the CF decay, the reconstruction efficiency is calculated using the efficiency of each bin of the $M^2(K^-\pi^+)$ versus $M^2(pK^-)$ Dalitz distribution [20], shown in Fig. 3, and weighting them by the number of events for the bin in real data. The relative difference between the reconstruction efficiencies, before and after this weighting, is 3.0%. For the

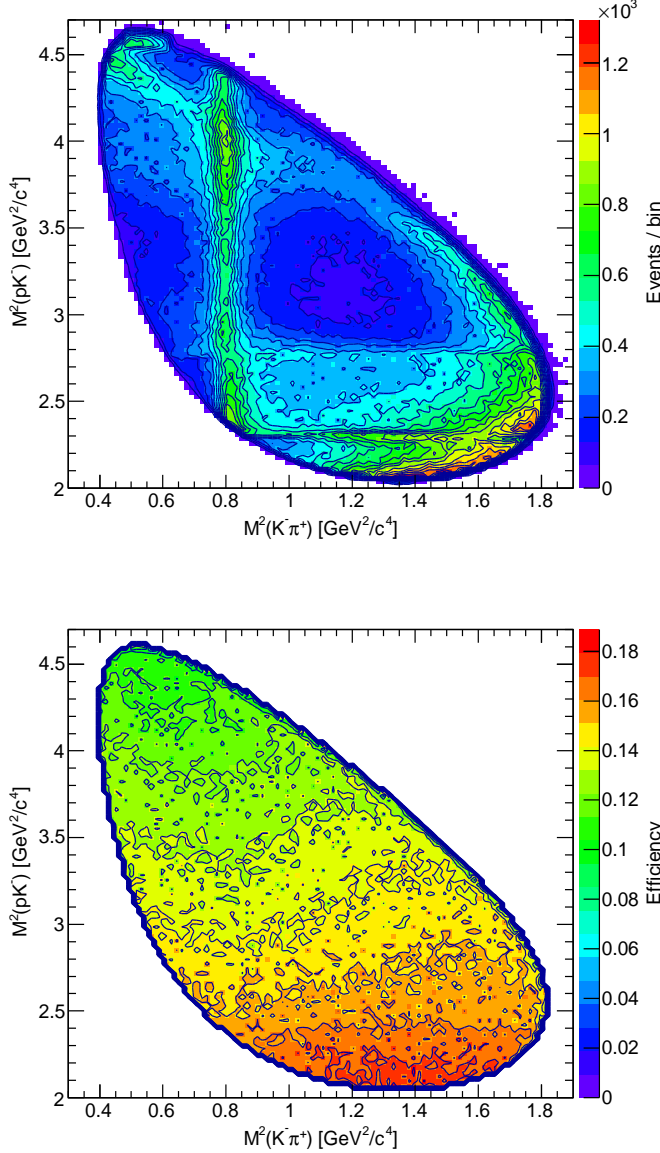


FIG. 3. Invariant mass squared of $K^-\pi^+$ versus pK^- within $2.2746 \text{ GeV}/c^2 < M(pK^-\pi^+) < 2.2986 \text{ GeV}/c^2$ in real data (top) and estimated efficiency using the MC (bottom). The bin widths of x and y axes are $0.016 \text{ GeV}^2/c^4$ and $0.027 \text{ GeV}^2/c^4$, respectively.

DCS decay, the largest relative difference (4.5%) between the efficiency of a subchannel and the overall reconstruction efficiency is taken as the efficiency uncertainty. The relative efficiency between the CF and DCS decays is 1.01 ± 0.05 , where the uncertainty is due to the uncertainty in the composition of the intermediate states.

The branching ratio, $\mathcal{B}(\Lambda_c^+ \rightarrow pK^+\pi^-)/\mathcal{B}(\Lambda_c^+ \rightarrow pK^-\pi^+)$, is $(2.35 \pm 0.27 \pm 0.21) \times 10^{-3}$, where the uncertainties are statistical and systematic, respectively. Sources of the systematic uncertainty and their values

TABLE I. Systematic uncertainties and sources.

Source	Uncertainty (%)
Background from SCS signal	± 2.3
Intermediate states	± 5.4
Binning and fit range (DCS)	± 5.5
Binning and fit range (CF)	± 0.6
PDF shape (DCS)	± 2.6
PDF shape (CF)	± 1.4
MC statistics	± 0.4
PID	± 2.2
Charge-conjugate mode	± 1.8
Total	± 9.0

are listed in Table I. The uncertainty from the binning and range of the fits is estimated by changing the bin width to $3 \text{ MeV}/c^2$ and adjusting the fitted range of the invariant mass distributions. The uncertainty due to the PDF shapes is estimated by changing the order of the polynomial background function, by changing the signal function to the sum of three Gaussian distributions, and by fixing the resolution of the signal function to the MC-derived resolution value. The PID uncertainty is determined by data-MC comparison of several control samples. We treat the relative efficiency difference between charge-conjugate modes as a systematic uncertainty.

The branching fraction of the CF decay, $(6.84 \pm 0.24^{+0.21}_{-0.27}) \times 10^{-2}$, was already well-measured in a previous Belle analysis [21]. Combining that with our measurement, we determine the absolute branching fraction of the DCS decay to $(1.61 \pm 0.23^{+0.07}_{-0.08}) \times 10^{-4}$, where the first uncertainty is the total uncertainty of the branching ratio and the second is uncertainty of the branching fraction of CF decay. This measured branching ratio corresponds to $(0.82 \pm 0.12) \tan^4 \theta_c$, where the uncertainty is the total.

In conclusion, the first DCS decay of a charmed baryon, $\Lambda_c^+ \rightarrow pK^+\pi^-$, is observed with statistical significance of 9.4σ . The branching ratio relative to its counterpart CF decay is $(2.35 \pm 0.27 \pm 0.21) \times 10^{-3}$, where the first uncertainty is statistical and the second is systematic. This corresponds to $(0.82 \pm 0.12) \tan^4 \theta_c$, where the uncertainty is the total uncertainty. Naïvely, this would indicate that the W exchange does not make a large contribution to Λ_c^+ decays.

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